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A THEORETICAL LIGHT-CURVE MODEL FOR THE 1999 OUTBURST OF U SCORPII

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ABSTRACT

A theoretical light curve for the 1999 outburst of U Scorpii is presented in order to obtain various physical parameters of the recurrent nova. Our U Sco model consists of a very massive white dwarf (WD) with an accretion disk and a lobe-filling, slightly evolved, main-sequence star (MS). The model includes a reflection effect by the companion and the accretion disk together with a shadowing effect on the companion by the accretion disk. The early visual light curve (with a linear phase of $t \sim 1-15$ days after maximum) is well reproduced by a thermonuclear runaway model on a very massive WD close to the Chandrasekhar limit ($M_{\rm WD} = 1.37 \pm 0.01\ M_\odot$), in which optically thick winds blowing from the WD play a key role in determining the nova duration. The ensuing plateau phase ($t \sim 15-30$ days) is also reproduced by the combination of a slightly irradiated MS and a fully irradiated flaring-up disk with a radius ~ 1.4 times the Roche lobe size. The cooling phase ($t \sim 30-40$ days) is consistent with a low hydrogen content $X \approx 0.05$ of the envelope for the $1.37 M_\odot$ WD. The best fit parameters are the WD mass $M_{\rm WD} \sim 1.37\ M_\odot$, the companion mass $M_{\rm MS} \sim 1.5 M_\odot$ ($0.8-2.0 M_\odot$ is acceptable), the inclination angle of the orbit $i \sim 80°$, and the flaring-up edge, the vertical height of which is ~ 0.30 times the accretion disk radius. The duration of the strong wind phase ($t \sim 0-17$ days) is very consistent with the BeppoSAX supersoft X-ray detection at $t \sim 19-20$ days because supersoft X-rays are self-absorbed by the massive wind. The envelope mass at the peak is estimated to be $\sim 3 \times 10^{-6} M_\odot$, which is indicating an average mass accretion rate $\sim 2.5 \times 10^{-7} M_\odot$ yr^{-1} during the quiescent phase between 1987 and 1999. These quantities are exactly the same as those predicted in a new progenitor model of Type Ia supernovae.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (U Scorpii)

1. INTRODUCTION

U Scorpii is one of the well observed recurrent novae, characterized by the shortest recurrence period (~ 8 yr), the fastest decline of its light curve (0.6 mag day^{-1}), and its extremely helium-rich ejecta (He/H~ 2 by number; see, e.g., Webbink et al. 1987 for summary). Historically, the outbursts of U Sco were observed in 1863, 1906, 1936, 1979, 1987, and the latest in 1999. Especially, the 1999 outburst was well observed from the rising phase to the cooling phase by many observers (e.g., Munari et al. 1999), including eclipses (Matsumoto & Kato 1999), thus providing us with a unique opportunity to construct a comprehensive model of U Sco during the outburst.

Our purpose in this Letter is to construct a detailed theoretical model for U Sco based on our light-curve analysis. A part of the method has been described in Hachisu & Kato (1999), in which they explain the second peak of T CrB outbursts, but we again briefly summarize it in §2, and will fully describe it in a separate paper. In §3, by directly fitting our theoretical light curve to the observational data, we derive various physical parameters of U Sco. Discussions follow in §4, especially in relation to the recently proposed progenitor model of Type Ia supernovae (SNe Ia).

2. THEORETICAL LIGHT CURVES

Schaefer (1990) and Schaefer & Ringwald (1995) observed eclipses of U Sco in the quiescent phase and determined the orbital period ($P = 1.23056$ days) and the Ephemeris (HJD 2,451,235.777 + $1.23056E$) at the epoch of mideclipse. It is very likely that the companion is a slightly evolved main-sequence star (MS) that expands to fill its Roche lobe after a large part of the central hydrogen is consumed. The phase duration ($\Delta\varphi \sim 0.1$) of the primary eclipses in quiescent phase indicates an inclination angle of $i \sim 80°$ (e.g., Warner 1995).

Our model is shown graphically in Figure 1. We have revised Kato's (1990) U Sco light-curve models in the following two ways: (1) the opacity has been changed from the Los Alamos opacity (Cox, King, & Tabor 1973) to the OPAL opacity (Iglesias & Rogers 1996) and (2) the reflection/irradiation effects both of the companion star and the accretion disk are introduced in order to follow the light curve during the entire phase of the outburst. The visual light curve is calculated from three components of the sys-

tem: (1) the white dwarf (WD) photosphere, (2) the MS photosphere, and (3) the accretion disk surface.

2.1. *Decay Phase of Novae*

In the thermonuclear runaway model (e.g., Starrfield, Sparks, & Shaviv 1988), WD envelopes quickly expand to $\sim 10 - 100\ R_\odot$ or more and then the photospheric radius gradually shrinks to the original size of the white dwarfs. Correspondingly, the optical luminosity reaches its maximum at the maximum expansion of the photosphere and then decays toward the level in the quiescent phase, keeping the bolometric luminosity almost constant. Since the WD envelope reaches a steady-state after maximum, we are able to follow the development by a unique sequence of steady-state solutions as shown by Kato & Hachisu (1994). Optically thick winds, blowing from the WD in the decay phase of novae, play a key role in determining the nova duration because a large part of the envelope mass is quickly blown off in the wind.

In the decay phase, the envelope structure at any given time is specified by a unique solution. The envelope mass ΔM is decreasing because of both the wind mass loss at a rate of $\dot{M}_{\rm wind}$ and the hydrogen shell burning at a rate of $\dot{M}_{\rm nuc}$, i.e.,

$$\frac{d}{dt}\Delta M = \dot{M}_{\rm acc} - \dot{M}_{\rm wind} - \dot{M}_{\rm nuc}, \tag{1}$$

where $\dot{M}_{\rm acc}$ is the mass accretion rate of the WD. By integrating equation (1), we follow the development of the envelope and then obtain the evolutionary changes of physical quantities such as the photospheric temperature $T_{\rm ph}$, the photospheric radius $R_{\rm ph}$, the photospheric velocity $v_{\rm ph}$, the wind mass loss rate $\dot{M}_{\rm wind}$, and the nuclear burning rate $\dot{M}_{\rm nuc}$. When the envelope mass decreases to below the critical mass, the wind stops, and after that, the envelope mass is decreased only by nuclear burning. When the envelope mass decreases further, hydrogen shell-burning disappears, and the WD enters a cooling phase.

2.2. *White Dwarf Photosphere*

After the optical peak, the photosphere shrinks with the decreasing envelope mass mainly because of the wind mass loss. Then the photospheric temperature increases and the visual light decreases because the main emitting region moves blueward (to UV then to soft X-ray). We have assumed a blackbody photosphere of the white dwarf envelope and estimated visual magnitude of the WD photosphere with a window function given by Allen (1973). The photospheric surface is divided into 32 pieces in the latitudinal angle and into 64 pieces in the longitudinal angle as shown in Figure 1. For simplicity, we do not consider the limb-darkening effect.

2.3. *Companion's Irradiated Photosphere*

To construct a light curve, we have also included the contribution of the companion star irradiated by the WD photosphere. The companion star is assumed to be synchronously rotating on a circular orbit and its surface is also assumed to fill the inner critical Roche lobe, as shown in Figure 1. Dividing the latitudinal angle into 32 pieces and the longitudinal angle into 64 pieces, we have also summed up the contribution of each patch, but, for simplicity, we neglect both the limb-darkening effect and the gravity-darkening effect of the companion star. Here we assume that 50% of the absorbed energy is reemitted from the companion surface with a blackbody spectrum at a local temperature. The original (nonirradiated) photospheric temperature of the companion star is assumed to be $T_{\rm ph,MS} = 4600$ K because of $B - V = 1.0$ in eclipse (Schaefer & Ringwald 1995; see also Johnston & Kulkarni 1992). Two other cases of $T_{\rm ph,MS} = 5000$ and 4400 K have been examined but do not show any essential differences in the light curves.

2.4. *Accretion Disk Surface*

We have included the luminosity coming from the accretion disk irradiated by the WD photosphere when the accretion disk reappears several days after the optical maximum, i.e., when the WD photosphere shrinks to smaller than the size of the inner critical Roche lobe. Then we assume that the radius of the accretion disk is gradually increasing/decreasing to

$$R_{\rm disk} = \alpha R_1^*, \tag{2}$$

in a few orbital periods, where α is a numerical factor indicating the size of the accretion disk and R_1^* is the effective radius of the inner critical Roche lobe for the primary WD component. The surface of the accretion disk absorbs photons and reemits the absorbed energy with a blackbody spectrum at a local temperature. Here, we assume that 50% of the absorbed energy is emitted from the surface while the other is carried into the interior of the accretion disk and eventually brought into the WD. The original temperature of the disk surface is assumed to be constant at $T_{\rm ph,disk} = 4000$ K including the disk rim. The viscous heating is neglected because it is much smaller than that of the irradiation effects.

We also assume that the accretion disk is axisymmetric and has a thickness given by

$$h = \beta R_{\rm disk} \left(\frac{\varpi}{R_{\rm disk}} \right)^2, \tag{3}$$

where h is the height of the surface from the equatorial plane, ϖ the distance on the equatorial plane from the center of the WD, and β is a numerical factor showing the degree of thickness. We have adopted a ϖ-squared law simply to mimic the effect of the flaring up of the accretion disk rim (e.g., Schandl, Meyer-Hofmeister, & Meyer 1997) and the exponent does not affect the disk luminosity so much mainly because the central part of the disk is not seen. The surface of the accretion disk is divided into 32 pieces logarithmically and evenly in the radial direction and into 64 pieces evenly in the azimuthal angle as shown in Figure 1. The outer rim of the accretion disk is also divided into 64 pieces in the azimuthal direction and 8 pieces in the vertical direction by rectangles.

We have reproduced the light curves in the quiescent phase (B-magnitude, Schaefer 1990) by adopting a set of parameters such as $\alpha = 0.7$, $\beta = 0.30$, a 50% irradiation efficiency of the accretion disk, and $i = 80^\circ$ for the WD luminosity of $\sim 1000 L_\odot$ ($A_B = 0.8$ and $d = 15$ kpc, or $A_B = 2.8$ and $d = 6$ kpc, see below), which

is roughly corresponding to the mass accretion rate of $\dot{M}_{\rm acc} = 2.5 \times 10^{-7} M_\odot$ yr^{-1} for the $1.37 M_\odot$ WD.

3. RESULTS

Figure 2 shows the observational points and our calculated V-magnitude light curve (solid line). To maintain an accretion disk, we assume a mass accretion rate $\dot{M}_{\rm acc} = 1 \times 10^{-7} M_\odot$ yr^{-1} during the outburst.

To fit the early linear decay phase ($t \sim 1-10$ days after maximum), we have calculated a total of 140 V-magnitude light curves for five cases of the WD mass: $M_{\rm WD} = 1.377$, 1.37, 1.36, 1.35, and 1.3 $M_\odot$, with various hydrogen content of $X = 0.04$, 0.05, 0.06, 0.07, 0.08, 0.10, and 0.15 of the envelope, where the metallicity $Z = 0.02$ is fixed, each for four companion mass of $M_{\rm MS} = 0.8$, 1.1, 1.5, and $2.0 M_\odot$. We choose $1.377 M_\odot$ as a limiting mass just before the SN Ia explosion in the W7 model ($M_{\rm Ia} = 1.378 M_\odot$) of Nomoto, Thielemann, & Yokoi (1984).

We have found that the early 7 day light curve hardly depends on the chemical composition and the companion mass but is mainly determined by the white dwarf mass. This is because (1) the early-phase light curve is determined mainly by the WD photosphere (Fig. 2, dotted line) and therefore by the wind mass loss rate and (2) the optically thick wind is driven by the strong peak of OPAL opacity, which is due not to helium or hydrogen lines but to iron lines (Kato & Hachisu 1994). Therefore, the determination of the WD mass is almost independent of the hydrogen content, the companion mass, or the disk configuration. The $1.37 M_\odot$ light curve is in much better agreement with the observations than are the other WD masses.

The distance to U Sco is estimated to be 5.4—8.0 kpc, as shown in Figure 2, if we assume no absorption ($A_V = 0$). Here, we obtain 5.4 kpc for the fit to the upper bound and 8.0 kpc for the fit to the lower bound of the observational points. For an absorption of $A_V = 0.6$ (Barlow et al. 1981), we have the distance of 4.1—6.1 kpc, and then U Sco is located 1.5—2.3 kpc above the Galactic plane ($b = 22°$). These ranges of the distance are reasonable compared with the old estimates of the distance to U Sco such as 14 kpc (e.g., Warner 1995).

To fit the cooling phase ($t \sim 30$—40 days after maximum), we must adopt the hydrogen content of $X = 0.05$ among $X = 0.04$, 0.05, 0.06, 0.07, 0.08, 0.10, and 0.15 for $M_{\rm WD} = 1.37$ $M_\odot$. This is because the hydrogen content X is equivalent to the mass of hydrogen burning in the envelope. Therefore, X determines the duration of hydrogen shell burning, i.e., the duration of the midplateau phase. For $X = 0.05$, the optically thick wind stops at $t = 17.5$ days, and the steady hydrogen shell-burning ends at $t = 18.2$ days. This duration of the strong wind phase is very consistent with the BeppoSAX supersoft X-ray detection 19—20 days after the optical peak (Kahabka et al. 1999) because supersoft X-rays are self-absorbed by the wind itself during the strong wind phase. It should be noted that we do not use this detection of the supersoft X-rays to constrain any physical parameters. Hydrogen shell-burning begins to decay from $t = 18.2$ days but still continues to supply a part of the luminosity; the rest comes from the thermal energy of the hydrogen envelope and the hot ash (helium) below the hydrogen layer. The thermal energy amounts to several times 10^{43} ergs, which can supply a bolometric luminosity of 10^{38} erg s^{-1} for ten days or so until $t \sim 30$ days, as seen in Figures 2 and 3.

The envelope mass at the peak is estimated to be $\Delta M \sim 3 \times 10^{-6} M_\odot$ for $M_{\rm WD} = 1.37 M_\odot$, $X = 0.05$, and $Z = 0.02$; thus, the average mass accretion rate of the WD becomes $\sim 2.5 \times 10^{-7} M_\odot$ yr^{-1} in the quiescent phase between 1987 and 1999, if no WD matter is dredged up into the envelope. Such high mass accretion rates strongly indicate that the mass transfer is driven by a thermally unstable mass transfer under the constraint that the companion star is a slightly evolved main-sequence star (e.g., van den Heuvel et al. 1992).

The wind carries away about 60% of the envelope mass, i.e., $\sim 1.8 \times 10^{-6} M_\odot$, which is much more massive than the observational indication of $\sim 1 \times 10^{-7} M_\odot$ in the 1979 outburst by Williams et al. (1981). The residual, $\sim 1.2 \times 10^{-6} M_\odot$, can accumulate in the WD. Therefore, the WD can grow in mass at an average rate of $\sim 1.0 \times 10^{-7} M_\odot$ yr^{-1}.

Our model fully reproduces the observational light curve if we choose $\alpha = 1.4$ and $\beta = 0.30$ during the wind phase and $\alpha = 1.2$ and $\beta = 0.35$ during the cooling phase for $1.37 M_\odot$ WD + 1.5 $M_\odot$ MS with $i \approx 80°$. Since we obtain similar light curves for four companion masses, i.e., 0.8, 1.1, 1.5, and 2.0 $M_\odot$, we show here only the results of $M_{\rm MS} = 1.5 M_\odot$. It is almost certain that the luminosity exceeds the Eddington limit during the first day of the outburst, because our model cannot reproduce the super Eddington phase.

4. DISCUSSION

Eclipses in the 1999 outburst were observed by Matsumoto & Kato (1999). The depth of the eclipses is $\Delta V \sim 0.5 - 0.8$, and it is much shallower than that in quiescent phase ($\Delta B \sim 1.5$, Schaefer 1990). Their observation also indicates almost no sign of the reflection effect by the companion star. Thus, we are forced to choose a relatively large disk radius that exceeds the Roche lobe ($\alpha \sim 1.4$) and a large flaring-up edge of the disk ($\beta \sim 0.30$). If we adopt a size of the accretion disk that is smaller than the Roche lobe, on the other hand, the companion star occults completely both the accretion disk and the white dwarf surface. As a result, we obtain a deep primary minimum as large as 1.5—2.0 or more.

We have tested a total of 140 cases of the set (α, β), i.e., 14 cases of $\alpha = 0.7 - 2.0$ by 0.1 step each for 10 cases of $\beta = 0.05 - 0.50$ by 0.05 step. The best fit light curve is obtained for $\alpha = 1.4$ and $\beta = 0.30$. Then a large part of the light from the WD photosphere is blocked by the disk edge, as shown in Figure 1. The large disk size and flaring-up edge may be driven by the Kelvin-Helmholtz instability because of the velocity difference between the wind and the disk surface. After the optically thick wind stops, photon pressure may drive the surface flow on the accretion disk (Fukue & Hachiya 1999), and we may expect an effect on the accretion disk similar to what the wind has, but it may be much weaker. Thus, we may have a smaller radius of $\alpha = 1.2$ but still have $\beta = 0.35$. A much more detailed analysis of the results will be presented elsewhere.

It has been suggested that U Sco is a progenitor of SNe Ia (e.g., Starrfield, Sparks, & Truran 1985) because its WD mass is very close to the critical mass ($M_{\rm Ia} = 1.38 M_\odot$) for

the SN Ia explosion (Nomoto et al. 1984). Hachisu et al. (1999) proposed a new evolutionary path to SNe Ia, in which they clarified the reason why the companion star becomes helium-rich even though it is only slightly evolved from the zero-age main sequence. A typical progenitor of SNe Ia in their WD+MS model, $M_{1,\mathrm{WD}} = 1.37 M_\odot$, $M_{2,\mathrm{MS}} \sim 1.3 M_\odot$, and $\dot{M}_{2,\mathrm{MS}} \sim -2 \times 10^{-7} M_\odot$ yr^{-1} just before the SN Ia explosion, has exactly the same system as U Sco. Thus, it is very likely that the WD in U Sco is now growing in mass at an average rate of $\sim 1 \times 10^{-7} M_\odot$ yr^{-1} toward the critical mass for the SN Ia explosion and will soon explode as an SN Ia if the WD core consists of carbon and oxygen.

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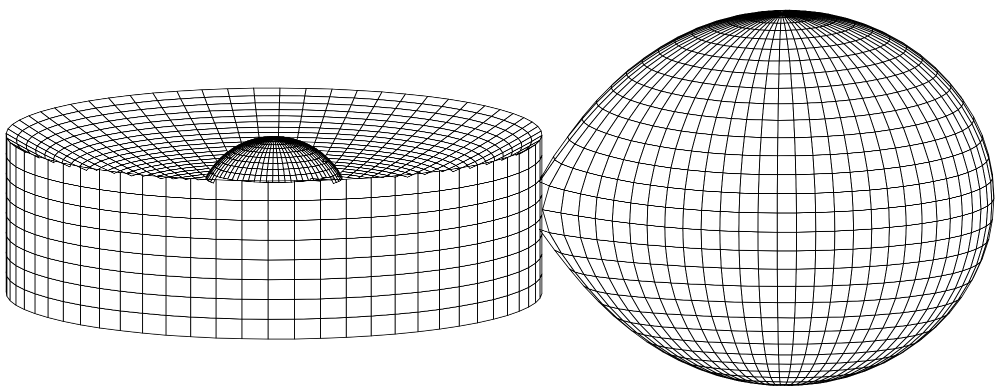

FIG. 1.— Configuration of our U Sco 1999 outburst model $t \sim 9$ days after the maximum, i.e., when the WD photosphere shrinks to $R_{\rm ph} = 1.0 R_\odot$. The cool component (right figure) is a slightly evolved MS ($1.5 M_\odot$) filling up its inner critical Roche lobe. Only the north and south polar areas of the secondary are heated up by the hot component (1.37 $M_\odot$ WD, left figure) because a large part of the light from the hot component is blocked by the flaring-up edge of the accretion disk. Here, the separation is $a = 6.87 R_\odot$, and the effective radii of the inner critical Roche lobes are $R_1^* = 2.55 R_\odot$, and $R_2^* = R_2 = 2.66 R_\odot$, for the primary WD and the secondary MS, respectively.

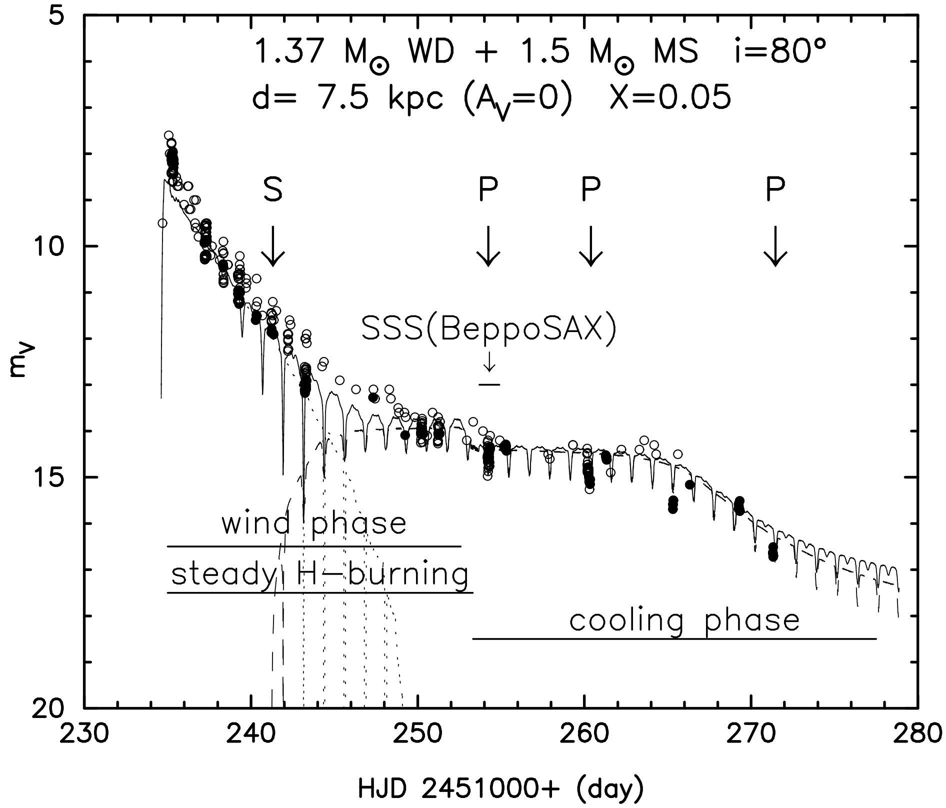

FIG. 2.— Theoretical light curve (solid line) plotted against time (HJD 2,451,000+), together with the observational points (the filled circles represent data taken from Matsumoto & Kato 1999, the open circles from the VS-NET archives), for $1.37 M_{\odot}$ WD + $1.5 M_{\odot}$ MS with an inclination angle $i = 80°$. The brightnesses of the white dwarf photosphere (dotted line) and of the accretion disk surface (dashed line) are also added. The distance to U Sco is estimated to be 5.4—8.0 kpc for no absorption ($A_V = 0$) but 4.1—6.1 kpc for $A_V = 0.6$. U Sco was detected by BeppoSAX as a supersoft X-ray source (SSS) 19—20 days after maximum (Kahabka et al. 1999). The capital letters "S" and "P" mean the secondary minimum and the primary minimum, respectively, in the eclipses observed by Matsumoto and Kato (1999).

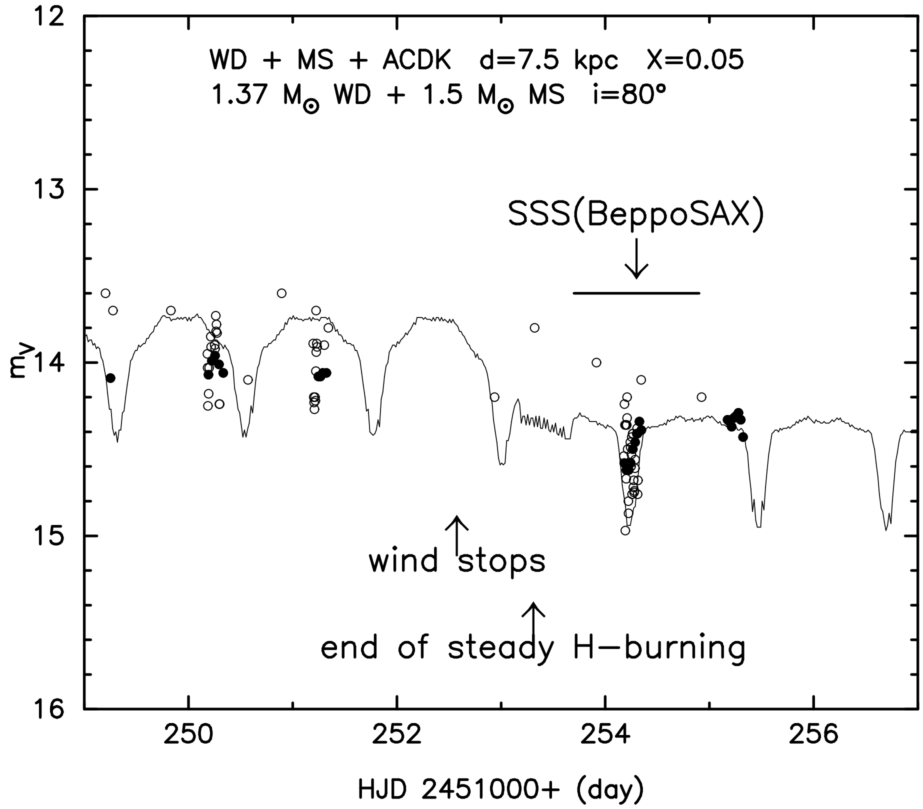

Fig. 3.— Same as Fig. 2, but for a part of the light curve that takes place during the transition from the wind phase to the cooling phase ($t \sim 14 - 22$ days). When the optically thick wind stops at $t = 17.5$ days, the photosphere of the white dwarf envelope drastically shrinks from $\sim 0.1 R_\odot$ to $\sim 0.003 R_\odot$ within 1 day. This makes a drop $\Delta m_V \sim 0.3$ near $t \sim 18$ days (HJD 2,451,253), which is followed by a further drop $\Delta m_V \sim 0.4$ caused by a reduction of the accretion disk (ACDK) size. The detection of an SSS by BeppoSAX is very consistent with the wind duration because supersoft X-rays emerge only after the massive wind stops.